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HIGH-DEFINITION PHOTOGRAPHY OF PROJECT ECHO I SATELLITE

Prepared for:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON 25, D.C.

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(NASA CONTRACT NASr-49(03))

By: R. H. Weitbrecht Jul. 1963 48p refs

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STANFORD RESEARCH INSTITUTE

MENLO PARK, CALIFORNIA

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By: *R. H. Weitbrecht*

SRI Project No. 3890

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ABSTRACT

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Results of the NASA-Lick Observatory-SRI cooperative project of high-definition photography of the balloon satellite Echo I are presented. Due to poor seeing as well as to photographic difficulties caused by the specular reflectivity of the object, efforts to delineate the shape of the balloon are inconclusive. A model experiment was undertaken to show what results would be obtained using a satellite coated with various proportions of specular and diffuse reflectivities.

Feasibility of photographing a satellite on a fly-by using a fixed telescope system with an image motion compensating camera is demonstrated. Furthermore, desirability of multiple exposures for identification of satellite images on film, comparisons thereof, as well as for separation from film defects is shown.

Author

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I INTRODUCTION

A. THE ECHO SATELLITE

In August, 1960, a 100-foot-diameter balloon was placed in a 1000-mile-high orbit under National Aeronautics and Space Administration auspices. One goal was to provide a passive radio/radar reflector for use by various radio research and communication groups working toward long-distance communications between points on earth, using this reflector as a relay point. Another goal—subtle and scientific in outlook—was that of studying characteristics of materials in the environment of outer space, as well as evaluating the effect of atmospheric drag on orbital parameters. At the time of launching, little information was available to predict what would happen to this satellite during launch and orbit—hence the great interest by varied groups of radio engineers, geophysicists, astronomers, and atmospheric physicists at the time. A six month's life was predicted for this object, after which it was expected that the balloon would be torn to pieces by the hostile environment of outer space or else dragged back into the atmosphere and burned up. However, Echo I is still in orbit; it may remain there for a number of years.

Echo I was launched by rocket from Cape Canaveral. The balloon was initially packed in a canister in the nose of the rocket so it would pass through the atmosphere with minimum damage to its fragile, aluminized Mylar skin. Once out of the atmosphere and in orbit, the canister was opened and the ballon allowed to inflate by means of sublimating material packed inside. The frontispiece is a photograph.* The picture shows the highly reflective "sun-spot" of solar reflection caused by the specular reflection characteristic of the metallic surface of the object. A great contrast range is involved; the bright area is obviously overexposed, while the faint outline of the rest of the balloon can be traced, showing such detail as the gores used in the construction.

Since the launching, radio fading phenomena have been observed during the balloon's employment as a passive radio reflector. This periodic

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* Of an Echo type test balloon taken during a suborbital ballistic test by a camera in launch vehicle.

fading suggested that the balloon had become deformed or had collapsed. This impression was reinforced by visual photographic observation showing similar periodic variations in brightness as Echo I traveled across the night sky. Sometimes variations would be small, at other times quite large, thus showing the influence of aspect on a distorted, revolving balloon with respect to radio signals or to solar-illuminated reflections. This created the great interest in obtaining meaningful photographs to ascertain the present shape of Echo I, if at all possible, with available optical equipment. Accordingly, arrangements were sought with an astronomical observatory having a long-focus telescope to undertake observing runs employing specially modified camera equipment.

B. PROJECT HISTORY

NASA approached Doctors S. Vasilevskis and A. E. Whitford of Lick Observatory and Stanford Research Institute with an idea of using the observatory's 36-inch refractor telescope, together with a suitably modified camera, to do this photography.

A contract was awarded to SRI on November 1, 1961, and work was immediately begun on the camera mount design, following essentially the same lines as those followed in the recently completed Lick Astrometric Camera, (SRI Project 3095).*

The camera construction and design problems are discussed in the succeeding sections, followed by sections on observations, results, and interpretation.

This project involved several month's effort, on part-time basis, of a model maker, a physicist, and an electronics technician. The relatively simple and straightforward camera system was designed with one mission in mind—that of obtaining and recording as sharply as possible images of the Echo I satellite as focused by the 36-inch refractor optics.

* References are listed at the end of the report.

Observations began in the summer of 1962 and were continued intermittently through fall of that year, as satisfactory ephemerides became available via TWX from Goddard Spaceflight Center, NASA, Greenbelt, Maryland. Approximately eight observing sessions resulted in photographic images of varying quality or in near misses. Of that number, a few have sufficient image quality on which to base conclusions. Observations were terminated in December. Dr. S. Vasilevskis and Mr. R. H. Weitbrecht served as observers during all these sessions.

II DESIGN OF PHOTOGRAPHIC EQUIPMENT

A. GEOMETRICAL OPTICS CONSIDERATIONS

As mentioned, Echo I is a 100-foot diameter balloon placed in a 1000-mile-high orbit. A near-overhead pass of this object will, in general, be the point of closest approach to the observing site, and hence where its angular size will be greatest. Computation shows that this angular size will be approximately 4 seconds of arc.

The 36-inch refractor telescope has a theoretical resolving power of 0.12 second of arc, a value which has been verified during visual double-star measurement work on nights with best seeing conditions. Thus, it appears that, ideally, approximately 40 "picture lines" should be resolved upon the object in each orthgonal coordinate, or a possible total of 1200 "picture elements." This refers to visual observation at the telescope, and requires a few seconds of perfect seeing. However, they are practically unattainable due to the high angular velocity of the satellite and the limited viewing area in the telescope. Only a fleeting glimpse of the object would be obtained. It would be the purest luck to be able to "see" the shape of the satellite, let alone the finer details such as surface roughness. Obviously the best recourse is to direct photography.

The Lick refractor has proved itself capable of producing good photographs when suitable color filters and isochromatic photographic emulsions are used. The instrument was designed and built some 75 years ago for use in visual work, and its objective lenses were corrected for a point-of-minimum focus at 5650 Angstroms. The focus degrades on either side of this yellow-green point, resulting in the familiar purple halo around stellar images when focused by this typical refractor doublet. Visually, this halo is not objectionable and can be ignored. But photographically it must be filtered out, because of the extreme blue-violet sensitivity of common photographic emulsions. A Schott type OG-1 filter glass accomplishes this when used with Kodak Type G emulsions. This is the general astrometric camera combination used for many years in double-star photography. A new 8-by-10-inch astrometric camera, fitted with automatic guiding features and this filter-emulsion combination has recently been completed and installed on the telescope.

In astrometric photography, the best images recorded, measure approximately 30 microns in size. This occurs during the best possible seeing nights, which are relatively rare. (Only five or ten nights per year are this good.) Practically speaking, seeing will degrade the "circle of confusion" to 60 to 100 microns in size.

It is of interest to determine the actual size of the best light-image when focused on an emulsion by the telescope. Since the scale is 11.7 seconds of arc per millimeter, and the theoretical resolving power is 0.12 second of arc, images would be 10 microns across. However, photographic emulsions are not that good—usually being limited to 40 lines/mm (25 microns min). Compounding the problem is the "turbidity" or light-scattering on the emulsion into areas surrounding the focused stellar image. Collectively, these effects limit the attainable minimum circle of confusion to about 30 microns.

Practically, 50 micron circle-of-confusion disks might be attained during good observing nights. At the focus of the telescope, Echo should yield an image of 340 microns diameter, or about 7 picture lines, for a total of 36 picture elements on the object itself. This should give an idea of the general shape of the balloon. This assumes, of course, that the visible area of the object is almost uniformly illuminated as far as the observer is concerned—"diffuse reflectivity."

B. ANGULAR MOTION CONSIDERATIONS

Echo travels across the visible sky at a relatively high angular rate—up to 30 degrees per minute of time. This means that it would be impractical to move a long, heavy telescope to follow such an object. Hence, the inevitable image motion at the focal plane of a telescope with fixed orientation must be compensated in other ways. This can be accomplished with a camera having continuously moving film. It should be feasible to "capture" at least one picture of the satellite during its travel time through the available viewing area at the telescope's tailpiece. Since the object is quite bright, the required exposure time will be on the order of $^1/_{100}$ second.

The object travels, as noted, at 30 degrees per minute of time. This amounts to 0.5 degrees or 30 minutes per second. The available viewing diameter of the Lick refractors is 12 inches at the tailpiece, which amounts to a viewing angle of 3560 seconds of arc—almost one degree. Thus, Echo will be visible at the telescope tailpiece for at least 2 seconds. However, the visibility time at the camera itself will be less, being governed not only by the available viewing aperture, but also by the refractor optics which has pronounced aberrations (coma) at the extreme edge of the tailpiece area.

The camera used on this project (see Part D) has a viewing aperture of 9 by 9 inches. It uses standard aero film, 9.5 inches wide, and its mechanism permits a film motion that can be set to match the motion of the image at the focal plane of the telescope for each satellite transit. In general, the object will be visible to the camera for a minimum of 1.5 seconds, but the images will be of usable quality for only a part of that time because of refractor optics aberrations.

J. R. Burke of NASA calculated from photographic and photometric considerations that an exposure of $^{1}/_{100}$ second should suffice to obtain a suitable impression on the usual aerial camera film emulsion.[2] Details were also given in Ref. 2 concerning the velocity of film motion required, suggested type of camera, and other data relative to this problem.

The simplest way of obtaining an impression of Echo on moving film would be to employ a focal plane shutter so timed as to travel across the viewing aperture during the time the image is in the center. This might be feasible if some sort of auxiliary timing mechanism were employed to trigger the shutter at precisely the proper time. However, this solution is a complicated one. The idea of multiple exposures, discussed next, seemed more practical.

C. MECHANICAL CONSIDERATIONS

Since it appeared too difficult to design a reliable device for triggering a single-exposure focal-plane shutter, within the available project funds and time, and since there was the possibility that the single image on a roll of film might be indistinguishable from a defect on the film surface, thereby making identification of the object uncertain if not impossible, it was decided to explore another approach.

The best manner of solving not only the timing problem but also the image identification problem appeared to be to make multiple exposures.

In this method the film velocity is adjusted to agree with the expected image motion at the time and place of the observation (Fig. 1). A rotary focal-plane shutter is interposed between the camera and telescope, near the focal plane of the latter. It rotates at 4 rps, and it carries a slit-sector, having a 10-degree opening. Exposures of about $^{1}/_{140}$ second are obtained, with a period between exposures of ¼ second. Notice

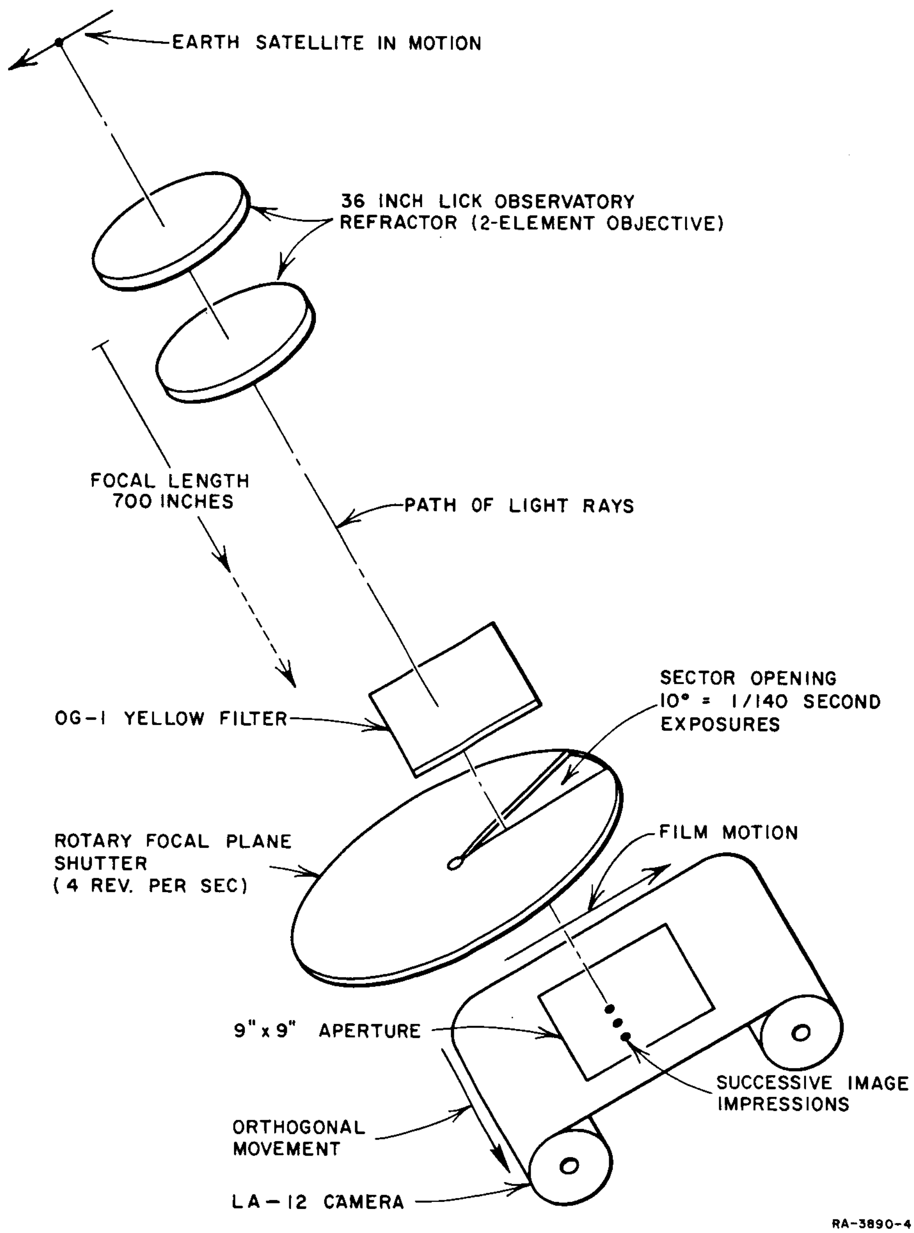


FIG. 1 OPTICAL PLAN OF THE TELESCOPE-CAMERA SYSTEM FOR PHOTOGRAPHING EARTH SATELLITE DURING A FLY-BY OBSERVATION

that eight or more successive exposures of "pictures" may be available during the time the image is within the 9-inch-square viewing aperture. These multiple exposures will not overlap each other on the film if a motion orthogonal to that of the image is introduced, in effect obtaining a row of image impressions across the film. This arrangement also facilitates identification.

This orthogonal motion can be obtained in either or both of two ways: by direct mechanical motion or by image drift during the observation. The camera can be aligned at such a skew angle that the image drifts sidewise with respect to film motion. Alternatively, side motion can be introduced. In general, however, the rate of such motion must be sufficiently low to separate the images yet not smear them, due to the motion itself.

To calculate the maximum rate for allowable smear, assume a circle-of-confusion of 50 microns diameter and allow not more than 25 microns smear during the exposure of $^1/_{140}$ second. Then, 25 microns × 140 = 3500 microns/second. At four exposures per second, image separations of approximately 900 microns are obtained. Since image sizes are about 300 microns, sufficient spacing will exist between successive images without overlapping or smearing. The observations shown here have been selected to satisfy that criterion insofar as image smears are concerned.

The distance of the focal plane from the Lick 36-inch telescope tailpiece is approximately 14.5 inches; this determines the over-all depth of the camera mount. This also necessitates a particular camera arrangement, since the accessories (base, focusing box, shutter, and filter) must go in a space less than 14.5 inches high.

Figures 2, 3, and 4 and Plates I, II, and III* show the essential mechanical details of the camera system. The main components are: (1) the mounting base, (2) the orthogonal base, (3) the focus box, and (4) the shutter case. The camera itself is discussed in Part D.

The mounting base fastens to the tailpiece of the 36-inch Lick refractor. The base consists of a machined 1-inch-thick aluminum alloy jigplate fitted with lugs that slip on bolts in the telescope's tailpiece. A 12-inch hole in the center of this base admits light from the telescope to the camera system. A pair of ¾-inch-diameter hardened steel rods

* Plates are grouped at the end of the report.

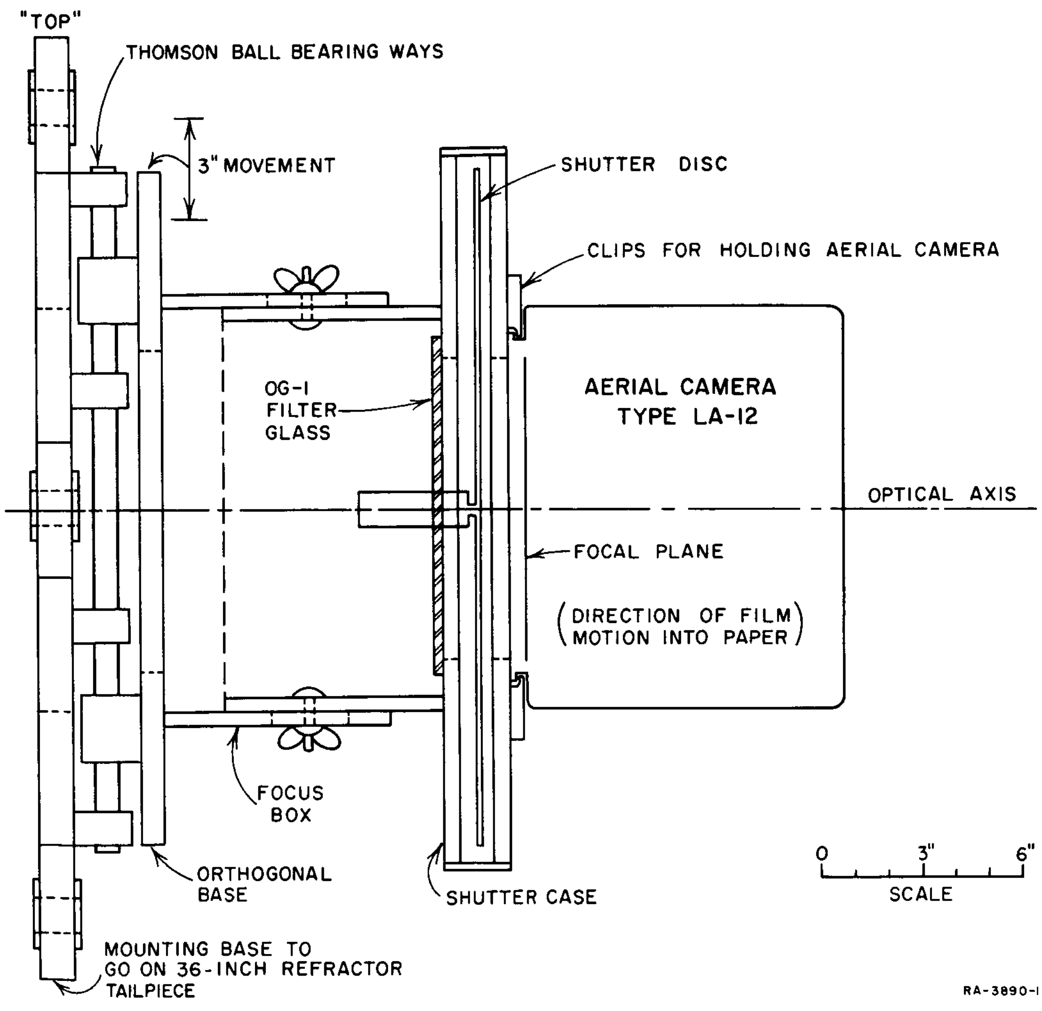


FIG. 2 CAMERA AND MOUNT, SHOWING ORTHOGONAL BASE, FILTER GLASS, AND SHUTTER SYSTEM

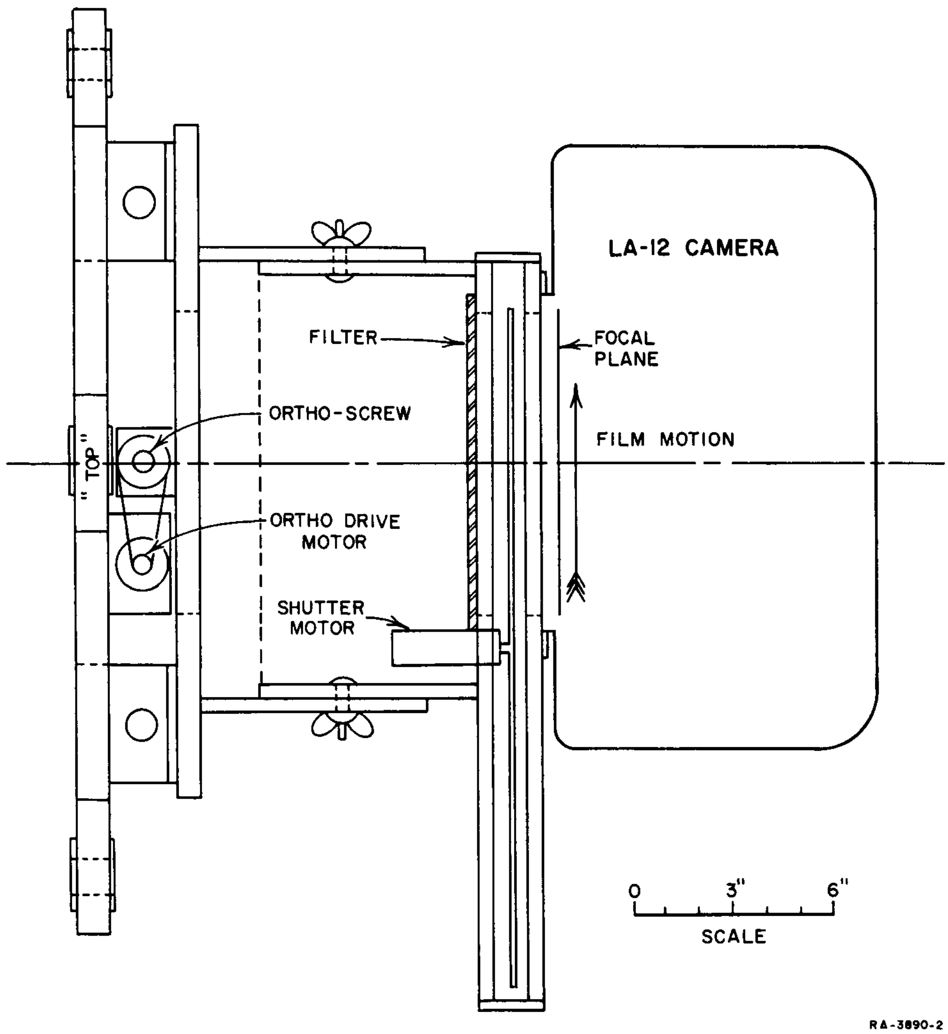


FIG. 3 CAMERA AND MOUNT, SHOWING ORTHOGONAL MOTION SYSTEM AND OTHER PARTS

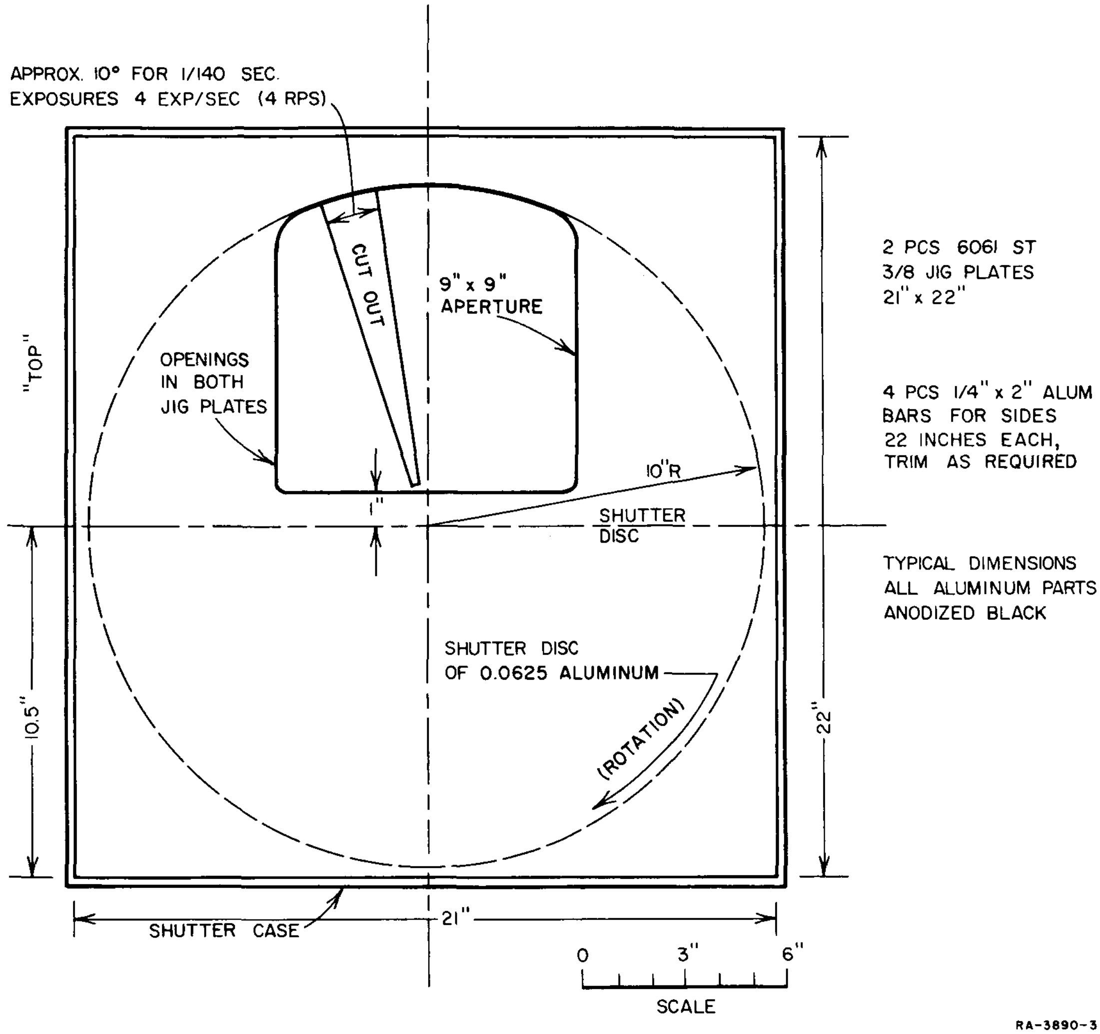


FIG. 4 APERTURE OF CAMERA SYSTEM, SHOWING SECTOR CUTOUT IN FOCAL PLANE SHUTTER DISK

are mounted along two opposite sides so as to straddle this opening; these rods constitute the ways for the base generating the sidewise motion to slide on.

The orthogonal base, of ¾-inch jigplate, carries a set of four Thomson linear ball-bearing bushings mounted on corners so arranged as to slide a maximum of 3 inches upon the pair of steel rods. This base is moved with respect to the other by means of a 28-volt dc gearhead motor driving a Saginaw ⅜-inch diameter ball-bearing screw-nut arrangement having a ⅛-inch lead, via a chain-driven 1:3 gear system. The motor, running at 100 rpm, generates a sidewise motion of 1700 microns/second. This rate is well within the maximum value of 3500 microns/second calculated from minimum-image-smear considerations, as mentioned earlier.

The focus box—actually two boxes telescoping 3 inches one into the other—is employed to permit focus adjustment between camera focal plane and telescope optics. With sliding surfaces well greased, the focusing is accomplished using the customary Foucault knife-edge procedure upon a suitable bright star. When exact focus has been established, the two boxes are clamped, using four wing nuts and bolts.

The shutter case encloses the 20-inch-diameter focal-plane shutter disc with sector cutout, and at the same time provides a suitable platform for the LA-12 camera. The jigplates used, as well as the focusing boxes, have been made thick though ($^3/_8$ inch) to carry the 55-pound weight of the camera with minimum distortion due to flexure.

The shutter disc is driven by a small 28-volt dc gearhead motor at rate of 4 revolutions per second. The sector cutout is 10 degrees, resulting in generation of $^{10}/_{360} \times$ 0.25 second = $^1/_{140}$-second exposures.

All aluminum parts have been anodized black to minimize light reflections inside the camera.

A Schott OG-1 yellow filter (glass) is fastened beneath the shutter case with clips so as to cover the 9 by 9-inch aperture through which light reaches the film. This filter, borrowed from the Observatory, renders the entire optical system isochromatic (at least over a narrow spectral range centered around 5650 Angstroms) when employed with Type G orthochromatic emulsion film. This filter-film combination so restricts the camera color response that telescope change-of-focus problems are minimized. Figure 5 details this color correction (from Ref. 1).

D. IMAGE MOTION COMPENSATING CAMERA

Several types of image motion compensating (IMC) cameras were available from government stock. Such cameras, used in aerial reconnaissance photography, are mounted in fast aircraft. Compensation is necessary to offset image motion in the focal plane introduced by aircraft motion. Hence, cameras of this type are designed to use roll film, of sufficient length to accomplish the photographic mission. Standard roll size is 9.5 inches by 100 to 200 feet long.

These cameras are of two general types: (1) panoramic, so a continuous strip view is obtained, and (2) autocycle, so successive snapshots are taken.

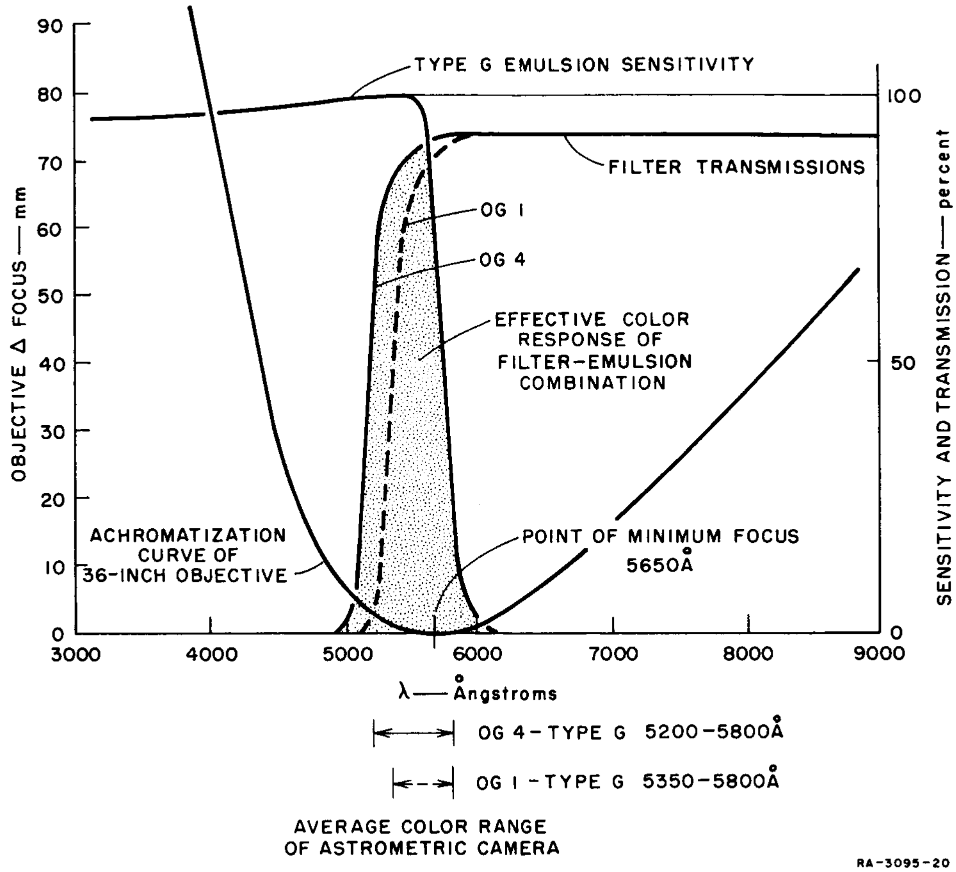


FIG. 5 AVERAGE COLOR RANGE OF TELESCOPE-CAMERA SYSTEM, USING OG-1 FILTER AND TYPE G EMULSION (from Ref. 1)

The LA-12 Camera Magazine,* manufactured by Chicago Aerial Survey Company, is of the autocycle type, convertible to panoramic type (continuous film movement, without rocker roller action). It has a 9 by 9-inch flat focal plane aperture on one side with a clip arrangement for fastening onto a standard K-37 aerial camera. A 28-volt governor-controlled motor drives a precision cone speed changer, producing film motion at rates from 0.5 to 15 inches per second. A 28-volt electric clutch operates the film metering rollers. A tachometer is part of the system; but it was not used. Instead, the rotation of a gear was measured by counting the number of gear teeth passing the pick-up head of a tape recorder, and applying the signal directly to an audio-frequency indicating meter. In this way, film motion rate could be set to a particular value for each Echo transit.

* Procured through advertisement by Thermoelectric Devices, Cambridge, Massachusetts in the December 1961 issue of *Sky and Telescope*.

The camera, stripped, weighs approximately 55 pounds. The simplest electrical equipment was sufficient for operating the entire camera system. Control switches applied power from a pair of 12-volt automobile batteries in series, and operated the motors and clutch on the camera, on the focal-plane shutter, and on the orthogonal leadscrew. The only electronic equipment needed was a Hewlett-Packard audio-frequency meter to monitor the output of the speed-sensing tape recorder head. This camera unit is shown in Plates I, II, and III, with various internal parts exposed.

E. PHOTOGRAPHIC MATERIALS

For such short-exposure photography, a low-contrast orthocromatic emulsion is required. The emulsion must be capable of a large range of density versus light exposure in order to handle the extremes of contrast involved in delineating the object images, *i.e.*, a low gamma. The LA-12 camera handles standard Aerecon spools (taking film 9½ inches wide and up to 200 feet long). All available Aerecon films were investigated. Since none of the regularly available films included orthochromatic emulsions, a special order was placed with the Eastman Kodak Company for a suitable Type G sensitized material, designated Linagraph Ortho on gray base. Five rolls were placed on standard Aerecon spools; each roll contained film 9½ inches wide by 150 feet. Film was refrigerated until used. Type G sensitization is necessary because of the need for drastic attenuation of light sensitivity to wavelengths longer than about 5800 Angstroms. Panchromatic emulsions are not suitable, because of the degradation of telescopic focus toward the red portion of the spectrum, as shown in Fig. 5. Of course, the Schott OG-1 filter attenuates the color response toward the violet end, giving a pass-band of 450 Angstroms to the film. Changes of focus in the telescope over this green-yellow portion of the spectrum are less than 1 millimeter. Dividing by the focal ratio of the telescope, f:19, results in a circle-of-confusion diameter of less than 50 microns, which is smaller than usually recorded photographically with the 36-inch refractor. Thus, "seeing" limits the quality of the resulting images, rather than telescope optical considerations.

Film was cut from the camera takeup spool after each observing session and developed with Kodak D-76, soft-working developer at 68 degrees F with development time held to 10 minutes; this yields a gamma of 1.04 with a density range of 80 to 1. Fixation and washing were standard. The resulting images were found adequate at the chosen shutter speed of 1/140 second and 4 exposures per second. In one of the last observing sessions, shutter speed was reduced to 1/35 second by means of a second sector cutout 40 degrees wide in the focal-plane shutter disk; resulting images were overexposed and enlarged due to turbidity and other factors.

It is interesting to note that image impressions were often inconspicuous, not even noticeable on casual examination of film against a bright light. It was necessary, therefore, to inspect all areas of the developed film with a magnifier before the characteristic row of image impressions could be located and verified. This confirms the necessity of resorting to a successive-exposures method to obtain multiple images, rather than attempting to capture a "snapshot" of Echo on each fly-by by some auxiliary shutter triggering system. Blemishes on the film would have rendered the identification of single images uncertain. Furthermore, the successive images can be compared with each other to evaluate detail change due to various extrinsic conditions, such as possible satellite aspect changes or seeing conditions.

F. CAMERA SETUP FOR OBSERVATIONS

After receipt of suitable ephemerides from NASA, Echo passages were selected and data processed to obtain camera position-angle settings, image velocities at the focal plane of the telescope, and the expected times of center-of-field-of-view crossings.

About an hour before predicted passage time, the 36-inch telescope was prepared by setting the Echo camera mount on the telescope tailpiece and determining focus by means of the Foucault knife-edge procedure, using a suitable bright star. The Observatory dome clock was calibrated to within 1 second by checking against the master clock (WWV-Naval Observatory verified). During the focus test on the bright star, star coordinates were compared with readings from the telescope circles to derive index corrections for application to Echo settings. Usually the selected bright star would be near the position in the sky where Echo was expected to cross the telescope's field of view to minimize variations from flexure of the telescope tube or mount.

Thirty minutes before passage time, the LA-12 camera, loaded with film, was clipped onto the mount and electrical power connections made to a pair of 12-volt automobile batteries in series. All electrical controls were operated and verified, namely the focal-plane shutter motor, the orthogonal-coordinate-motion motor, the LA-12 motor drive, and the electromagnetic clutch.

During the electrical system check, the Hewlett-Packard audio-frequency meter was turned on and connected to the tape recorder pickup head. The entire equipment, previously calibrated, was found to provide an audio-frequency of 1080 cps for film movement of 10 inches per second. During speed setting for the particular Echo passage involved, the camera motor was energized and allowed to come up to speed; thereupon the precision speed-changer device (a pair of cones with an idler wheel in a box, driven by the motor itself) was adjusted to produce the proper frequency. The camera has an electromagnetic clutch which initiates film movement when energized; during other tests it was found that the load thrown upon the drive mechanism during film movement did not cause more than 0.5-percent variation in motor speed. Hence, it was sufficient to run only the motor and set its speed without engaging the film motion clutch, thus conserving film.

The telescope was pointed to the area where the ephemeris computation indicated that Echo should be at the appointed time. Telescope settings were corrected for circle index errors, as determined from measurements made while focusing the camera on a bright star of known position.

The 36-inch telescope has a new set of high-precision setting dials that give Right Ascension accurate to a few seconds of time, Declination to better than a minute of arc, Hour Angle to a few seconds of time, and Camera Position Angle to a minute of arc. With the corrections for circle-index errors, telescope position settings should not be in error by much more than 1 minute of arc. At the focus of the telescope, this 1 minute corresponds to a displacement of 0.2 inch on the focal plane, which incidentally is contained within the 9 by 9-inch dimension of the LA-12 camera aperture. Atmospheric refraction error was negligible, inasmuch as observations were confined to elevation angles over 40 degrees.

A small vacuum pump was attached to the camera to keep the film against the focal-plane platen. The vacuum was adjusted by means of an air leak into the system, that maintained enough vacuum behind the film to pull it against the platen and still not unduly hamper film movement.

This procedure was followed because during first runs the film was whipping away from the platen by as much as 1 or 2 mm.

G. OBSERVATION PROCEDURE

Two observers operated the equipment. One observed through a low-powered finder telescope and the other through a high-powered finder (approximately 4-inch aperture); both on the side of the 36-inch refractor.

One observer announced the initial appearance of Echo at the edge of the 2-degree-wide, low-power field of view.

The other then engaged the electromagnetic clutch, starting the film and the orthogonal drive motor. The camera remained energized during the period when Echo was visible to the second observer in the higher-powered finder, and a few seconds longer. The telescope was disturbed as little as possible during the exposure.

The exact time of transit was recorded and compared with the predicted time for that passage.

III OBSERVATIONS

A. SEEING EFFECTS

Most of the recorded images were about 100 microns in diameter, appreciably smaller than expected, considering that the fully inflated balloon should show images roughly three times larger. There are, however, marked differences between successive ¼-second images. Should these differences be ascribed to viewing a "rapidly rotating crumpled aluminumized object?" This cannot be: Rotation of the balloon must be relatively slow, not only from dynamic considerations, but from observation with a wide-angle short-focus camera showing that Echo's trail exhibited relatively slow variations in brightness as it crossed the sky.

Exposures of a bright star, such as Vega (alpha Lyrae), were taken with camera telescope driven at sidereal rate. The star was centered near the edge of the field of view of the camera; the focal-plane shutter and the orthogonal motor drive were energized. The film was not moved internally by the film drive mechanism; instead, a portion was fixed and held against the platen by the vacuum pump. A series of ¼-second-spaced impressions of the star's image were flashed onto the film with 1/140-second exposures. A row of successive image impressions was thus generated on the film to simulate a similar row of successive images from Echo. Observing conditions were controlled as close as possible to afford a comparison between images from a star (essentially a point-of-light source) and from the balloon (a light source having an appreciable disk). This star observation served as a control that permitted definite separation of seeing effects from aspect effects on the satellite.

During the latter part of the observing program, such star runs were included. Some were taken immediately after the focusing check upon Vega; others were taken on the same star immediately after observation of Echo passage. A number of star-impressions were thus obtained, typically as shown in Plate IV. The upper row of impressions were taken under conditions of average seeing; stellar images measure 100 microns. (Ignore the wavy series of images; this was due to telescope sway and does not affect individual image quality.) The lower row of Plate IV was taken during poor seeing and is a convincing demonstration of the influence of seeing on image quality; image sizes measure 200 microns across. Each image differs from its preceding or following images in internal detail, evidently because of variations in seeing as perceived immediately in front of the telescope aperture.

The recently completed Lick Astrometric Camera system yields stellar image recordings of 80 to 100 microns diameter during good observing nights. Half-hour exposures are taken with automatic guiding; hence, each stellar image recording is an integrated impression upon the photographic emulsion of the star beam as focused thereon during the exposure interval. Sometimes, during periods of best seeing, image size decreases to 60 microns. Naturally, such occasions are quite rare and unpredictable; perhaps for only about 10 percent of available observing time are seeing conditions such that the telescope system can photograph down to its theoretical optical-photographic revolving limit.

The 36-inch telescope has been employed for some years in a double-star photography project. This was an astrometric program during which selected double stars were photographed using a multiple-exposure technique. Individual exposures thus taken were of a few seconds duration, usually, with the plate moved sideways between exposures to generate a row of image-impressions for later measurement of position angle and distance between *A* and *B* components. Thousands of such plates have been taken, and inspection indicates that stellar image sizes are as small as 30 microns and have an average diameter of 60 to 80 microns.

In summary, the optical performance of a long-focus, large-aperture, telescope-camera system is limited by seeing conditions since the equipment is located at the bottom of a virtual ocean of turbulent atmosphere. Practically speaking, the "seeing disk" (or circle of confusion) measures 1 second of arc under average seeing conditions. Thus, the telescope aperture might as well be of the order of 4.5 inches, rather than 36 inches. The larger aperture just takes in more of the small air cells (dimensions of a few inches to feet) that refract and confuse the light rays from the object to the telescope focus. The only benefit that accrues from the use of large apertures is their large light-gathering power, a factor that helps in reduction of photographic exposure time. Only at times are we fortunate enough to have seeing conditions that permit the fullest resolving power capacity of a large-apertured telescope to be utilized.

B. PLATES PRODUCED BY THE CAMERA

Out of the series of photographs, several are included in this report. These photographs, enlarged 40 diameters, are shown in Plates V, VI, VII, and VIII. Their data follow below:

Plate V:	1962 Oct. 8	2^h40^mUT	All evening passes, with slant range close to 1600 km.
Plate VI:	1962 Oct. 23	(First evening pass)	
Plate VII:	1962 Oct. 24	2^h14^mUT	
Plate VIII:	1962 Oct. 25	3^h21^mUT	

Other results are contained in two interim reports that have already been forwarded to NASA in connection with this photographic work. A preliminary report, dated October 4, 1962 contained inconclusive data, due to excessive camera sidewise motion that smeared the images. It served, however, to demonstrate the feasibility of the technique of photographing a satellite using a moving-film camera mounted on a suitable long-focus fixed astronomical telescope, for each fly-by of the object concerned.

A second report, dated October 9, 1962, gave better results; Plate V, above, is reproduced from it. The other three plates are results of a later series of observations and have not been reported previously. These three also contain recordings of a bright star for comparison with the satellite images. Plate V can therefore be evaluated by comparing it with Plates VI, VII, and VIII.

Plate IV, showing images of the star Vega under varied seeing conditions, has already been discussed. All plates are to same scale: 40-diameter enlargements from the original film negatives. In the case of the last three plates, satellite and stellar images are shown side by side for comparison.

C. DISCUSSION OF OBSERVATIONS

1. General

Observations were made at a time when there was about a 90-degree angle at the observing location between the sun and the satellite. Thus only one-half of the entire possible visible satellite disk was illuminated, similar to viewing the moon at first quarter. Indeed, the satellite appears as in the Frontispiece. It shows approximately a half disk, faintly illuminated because of its diffuse reflectivity. There is also an intense solar reflection point on the disk due to specular reflection from the mirror-like surface of the aluminized Mylar skin.

Viewed from the front, with sun behind the observer, the entire disk would appear uniformly illuminated except for a bright spot at the center. The dimension of this bright spot can be calculated from geometric optics considerations, approximately 2.6 inches diameter. The object is, of course, considered as a convex mirror having a negative focal length; hence the image is virtual. Viewed during actual observation with a 90-degree angle between sun-satellite-observer, there is a foreshortening which amounts to 2.6 tan 45° = approximately 1.8 inches on the disk in the solar direction. In a direction at 90 degrees with respect to solar direction the image is 2.6 inches wide. This yields an elliptical solar reflection area, quite distinctly seen in the Frontispiece.

The aluminized Mylar surface is not perfectly smooth; hence a combination of specular and diffuse reflectivities is involved in this solar reflection area. This makes the dimensions of this area appreciably larger; perhaps ten times as large or 18 by 26 inches. As Burke has pointed out,[2] this area would still not be resolvable with a 36-inch telescope in an ideal location, having perfect optics. The problem then is to be able to photograph the faint outline of the diffuse-reflected area of the disk, yet suppress the glare effect due to the intense specular reflection of the solar reflection spot. The balloon, if fully inflated, is 100 feet in diameter; its uniformly illuminated surface would be perceivable as a disk of 4 seconds of arc in a telescope and hence be photographable for a reasonable interpretation as to actual shape inasmuch as the average seeing disk is 1 second of arc.

The resolving power and sharpness of a photographic material are conditioned primarily by two factors: the turbidity and the inherent contrast of the emulsion. The turbidity is dependent upon two factors: the light-scattering power and the light-absorbing power of the emulsion. The spread of an image with an increase in exposure is a direct measure of turbidity. It is well known that if the image of a point upon a photographic plate is given a series of increasing exposures, the diameter, d, of the photographic image will not be its true geometric size, but will be given very closely[3] by

$$d = a + b \log E \quad .$$

Here, a and b are constants, the latter giving a measure of the turbidity of the emulsion, and E is exposure.*

In astronomical photographic photometry, image spread is used for the evaluation of stellar magnitudes by the measurement of the diameter of the star image. In fact, during our observations a longer exposure was made of the balloon in hope of reaching the fainter illuminated area. One observing run had a second sector cutout in the focal plane shutter for $^1/_{35}$-second exposures that was alternated with $^1/_{140}$-second exposures. Plate IX presents the result of a series of exposures on the star Vega; again 40-diameter enlargement. On this basis we perceive that the longer-exposed images are just about double in diameter the shorter-exposed images. Measurement shows that the longer-exposed images are 330 microns across, while the $^1/_{140}$-second images are about 180 microns. Roughly a 4x increase in exposure results in a doubling in image size; image size still varies from one exposure to the next. We are still not able to perceive a definite balloon shape from visual inspection of the series of images obtained. In other words, the inherent characteristics of turbidity and limited contrast range of available photographic emulsions, as well as seeing conditions, have hindered efforts to obtain meaningful photographs of Echo I.

It is interesting to note that the specular reflection spot on the balloon's aluminized Mylar skin has a relatively small diameter, comparable in angular size to the disks of some of the larger and nearer stars. Thus the object exhibits some of the characteristics of a bright star in the sky, *i.e.*, scintillation. Looking at the object and star impressions in Plates V-VIII inclusive, we are forced to conclude that both sets of images look essentially alike, and that we have no definite index to differentiate balloon images from star images.

2. Plate V

A series of some ten exposures were taken of the satellite alone; no star images are available for comparison. This was a good pass insofar as the camera was concerned; the images were obtained as the object image passed centrally through the viewing aperture of the camera from

* Defined as light intensity times time.

one side to the other. The four or six images in the center of the spread can be evaluated while the rest on the ends should be ignored; they are obviously affected by telescope aberrations, such as coma. Typical image size here is 180 to 200 microns; the individual images, taken ¼ second apart, are distinctly different from each other. This is probably due to poor seeing.

3. PLATE VI

This is a fair recording of the satellite. Images were captured near the edge of the moving 9.5-inch film material; hence they are softened by telescope aberrations due to the fact that they were some 4 inches away from the telescope's optical axis at the focal plane. The images of Vega are sharp and distinct, showing "considerable detail"* due to atmospheric turbulence (poor seeing). Comparison between the two sets of images leads us to conclude that they are quite similar and indistinguishable insofar as satellite aspect or shape is concerned. Typical image size is the same as in Plate V, *i.e.*, 190 microns. Exposures in both Plate V and VII are 1/140-second repeated ¼ second apart.

4. PLATE VII

Relatively speaking, this is one of the best plates. Seeing was better during this time, with image sizes about 100 microns. Echo images are grouped in a small area due to insufficient sidewise motion in the camera system during this pass; however, images on the perimeter of the area can still be compared with recordings of Vega. Both sets of images are very much alike and, as usual, affected by seeing variations (1/140-second exposures, 1/8 second apart).

5. PLATE VIII

Another good plate. Seeing was fair during this pass, with image sizes capable of being evaluated. The series of satellite images are best in the center of the spread; those on the ends are affected by telescope aberrations. Satellite images are noticeably softer than stellar images, probably due to difference in exposures involved. Seeing variations can be traced from exposure to exposure; these exposures were 1/8 second apart (still the same 1/140-second exposures).

* "Considerable detail"—showing definite air pockets, cells, waves, etc. as frozen onto the photographic film during each short exposure.

D. A MODEL EXPERIMENT

J. R. Burke of NASA, in his report to L. Jaffe,[2] referred to a model experiment in which a final image is produced to simulate the image from a full-scale photographic effort. In view of the inconclusive result of our photographic attempts to define the finer features of Echo I, we undertook a series of photographic tests of models in the laboratory to find out what would be shown in the final images thus reproduced.

Four $^7/_8$-inch-diameter, highly polished, steel bearing balls were used. Their surfaces were treated in various ways:

> Ball 1 was thoroughly sandblasted; this yielded an essentially uniform gray surface having a maximum of diffuse reflectivity and a minimum of specular reflectivity.
>
> Ball 2 was partially sandblasted, thus increasing the proportion of specular reflectivity as against diffuse reflectivity.
>
> Ball 3 was left as is, having at least 95-percent specular reflectivity considering it as a reflecting surface akin to silver or aluminized telescope mirror with 5-percent loss.
>
> Ball 4 was treated with a special spray used by photographers to tone down harsh highlights on highly polished surfaces of subjects being photographed.

These four steel balls, thus treated, were arranged in a row, with Ball 1 at the top and Ball 4 at the bottom. Plate X shows the balls placed under full sunlight illumination. The background area was made as dark as possible by enclosing the area in a dark chamber with a slit that allowed sunlight on the balls alone. Considering atmospheric absorption, this experiment should be representative of the full-scale effort except that seeing is eliminated as a factor—thus permitting us to determine the final result using perfect optical conditions.

A 35-mm camera, having a 55-mm focal-length lens and a focal-plane shutter, was placed on a tripod 12.2 feet from the model $^7/_8$-inch balls. These dimensions were such to provide images that would have been similar to Echo I observed under perfect conditions using the 36-inch refractor. Image size, from geometrical considerations, would have a maximum diameter of 330 microns on the film emulsion.

Using Kodak Linagraph Ortho film, similar to that used in the full-scale experiment, a series of exposures from $^1/_{1000}$ to 1 second were taken on twelve successive frames with an aperture stop of f/22. Further, this series was repeated in several different views to simulate various satellite viewing aspects. The exposures of 1/125, 1/250, and 1/500 second are shown in Plate XI. These exposures were selected as being most like the actual ones during a full-scale experiment. The longer-exposure images were overexposed, while the 1/1000-second exposures were greatly underexposed. The photographs depict what happens when solar-illuminated steel balls having different reflective surfaces are photographed against a dark ("sky") background. This plate is a 40-diameter enlargement from the original negatives, and thus may be compared with results obtained with the 36-inch telescope-camera system on Echo I. The scale is 250 microns per centimeter on Plates IV through XI inclusive (except for the picture of the steel balls in Plate X).

From Plate XI, it is interesting to note the definite disk of Ball 1 is readily perceptible from all four viewing angles; this is the ball with the gray diffuse reflective surface. Ball 3, with the intense specular reflection, cannot be recognized as a definite disk; the light-spot measures some 30 microns on the original negatives. Increasing exposure by a factor of 4 practically doubles Ball 3's reflection spot to 60 microns, thus showing the effect of turbidity in the film emulsion.

The other balls, having more or less even diffuse and specular reflectivities, show up on the film emulsion in varying degrees; the elliptical reflective spot is most like the one shown in the Frontispiece. The increase in size with increasing exposure is quite pronounced on these Balls, 2 and 4. The surrounding diffuse reflective areas are not as easy to perceive as Ball 1. Further increase in exposure increases the light reflective spot even more; at 1/125 second, Ball 4 has an image diameter of approximately 100 microns.

From all viewpoints, the fourth ball, with the special photographer's antiglare spray treatment, is most like the actual object, the satellite. This view could be compared with published NASA photographs of the inflated Echo prototype balloon inside a hangar.

Drastic increase in exposure brings out the diffuse reflected area on the fourth ball; with the camera this required exposures of the order of 1/15 second. Whether the full-scale experiment would have succeeded using a longer exposure, such as 1/15 second, is problematical because of the seeing- and turbidity-caused star-image enlargements so plainly shown in Plate IX, not to mention extensive camera modification needed for such long exposures.

IV SUMMARY AND CONCLUSIONS

A. SUMMARY

The results of this high-definition photography of Echo I using the 36-inch Lick refractor must be regarded as indeterminate. The "successful" observations have been too few in number because of the limited observing period. Seeing conditions were poor during most of this period (Autumn, 1962), and only a portion of the total time was available for this project since the telescope was in use for other Observatory work.

On most nights, the seeing was too poor to enable the actual shape of the balloon to be resolved at all. The spreading of the resulting image with increasing exposure obscured the fainter area of the object, and atmospheric turbulence (seeing) entered as a limiting factor. However, there were some rare occasions when seeing was satisfactory. We were unable to take many photographs for two reasons: To capture Echo I image on the center of the film aperture area, the satellite's path had to be known within 1/6 degree (10 minutes of arc) and its time of passage within 30 seconds. This is probably orders of magnitude more accurate than is required for radio use of the satellite, and hence we had a problem in getting sufficiently accurate data from NASA. Also this ephemeris data had to be updated and delivered to us the day of the intended observation, and getting this communication to us seemed to be a problem. The delay of even one day between receipt of ephemerides and observational work was important enough to allow orbital data to become inaccurate due to cumulative errors entering into the orbit computation from such factors as precession and atmospheric drag.

Lick Observatory extended their cooperative observing time from the planned termination date of October 15, 1962 to the end of November to permit us to undertake some further photography, resulting in the relatively excellent series of October 23-24-25. Furthermore, some experiments were undertaken with varied exposures later in the extended period, to evaluate effect of exposure variation upon image quality, the result being Plate IX.

It was thought there was not enough magnification in the optical system to enlarge the optical image in order to separate the fainter diffuse-reflection area more with respect to that due to the solar-illuminated specular reflection. However, it appears that the main problem is seeing conditions, and any further optical magnification would only increase the "noise" due to this condition, as Plates IV and IX so well show.

In summary, these photographic results are inconclusive. We have had too few successful observing sessions. Therefore, it was not possible to evaluate results and change parameters accordingly. Communication difficulties, as well as inaccurate ephemerides, have hampered and delayed our project. Furthermore, seeing during Fall at Lick Observatory is rather variable and unpredictable. Perhaps an intensive observing program, using cine technique with a proper long-focus reflector (say a 36-inch Cassegrain) mounted so as to precisely track Echo across the sky, would be more successful. An optical-visual integration of a great many snapshot frames superimposed might yield a better idea of the shape of this satellite. Such techniques have been used to obtain better defined planetary photographs at Lowell and Mount Palomar Observatories. A familiar example is a movie; individual frames may be quite grainy, but when they are projected at normal frame rate, the persistence of vision eliminates the "noise" inherent in film grain and delivers a sharper impression.

B. CONCLUSIONS

The photographic effort to obtain meaningful pictures of the Echo I balloon and thus define its present shape and condition was hindered by photographic-optical difficulties introduced by the object's reflectivity characteristics (mainly specular) as well as by seeing conditions. A more definite impression as to the object's shape might be obtained by an optical-visual integration of a great many frames or exposures on the object taken during better seeing conditions, preferably using a special large-apertured, long-focus tracking telescope equipped with a motion-picture camera system.

The feasibility of image capture on film of an earth satellite by using a fixed-oriented long-focus telescope system equipped with an image motion compensating (moving film) camera and a high-speed shutter system has been demonstrated. Furthermore, the desirability of successive exposures on the optically focused image has been shown, since this procedure enables separation of images from film-defect spots and aids in evaluation of the image for surface details.

The optical disturbances introduced by turbulence in the atmosphere—generally referred to as astronomical seeing—set a definite limit on the ability of a large-aperture (over 10 inches, say) telescope to reach its theoretical resolving power on objects outside the atmosphere. Seeing is highly variable and unpredictable, depending on weather and other conditions. It is apt to be better at very-high-altitude observing locations, such as mountain tops or balloon-borne telescope systems, such as Stratoscope.

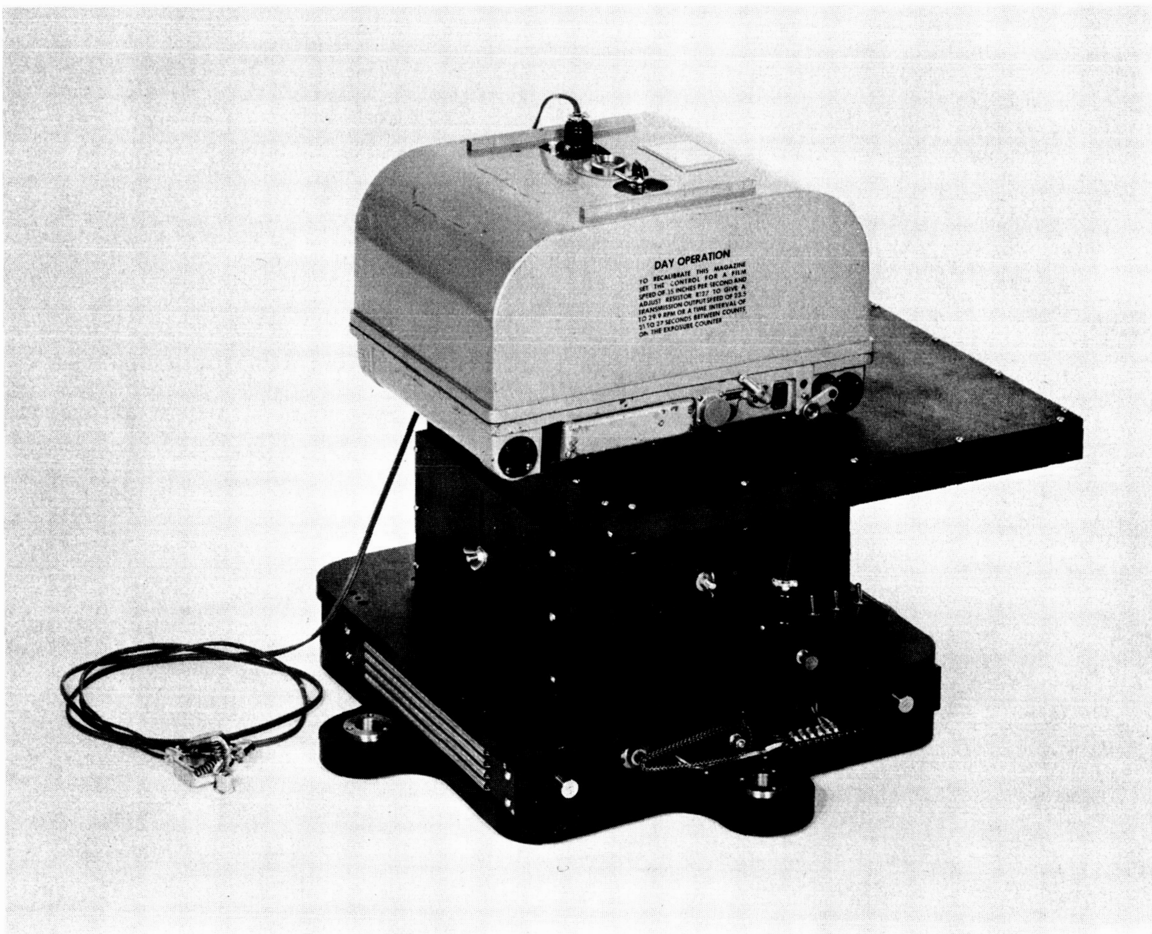


PLATE I VIEW OF CAMERA APPARATUS; LA-12 IMC CAMERA IN PLACE

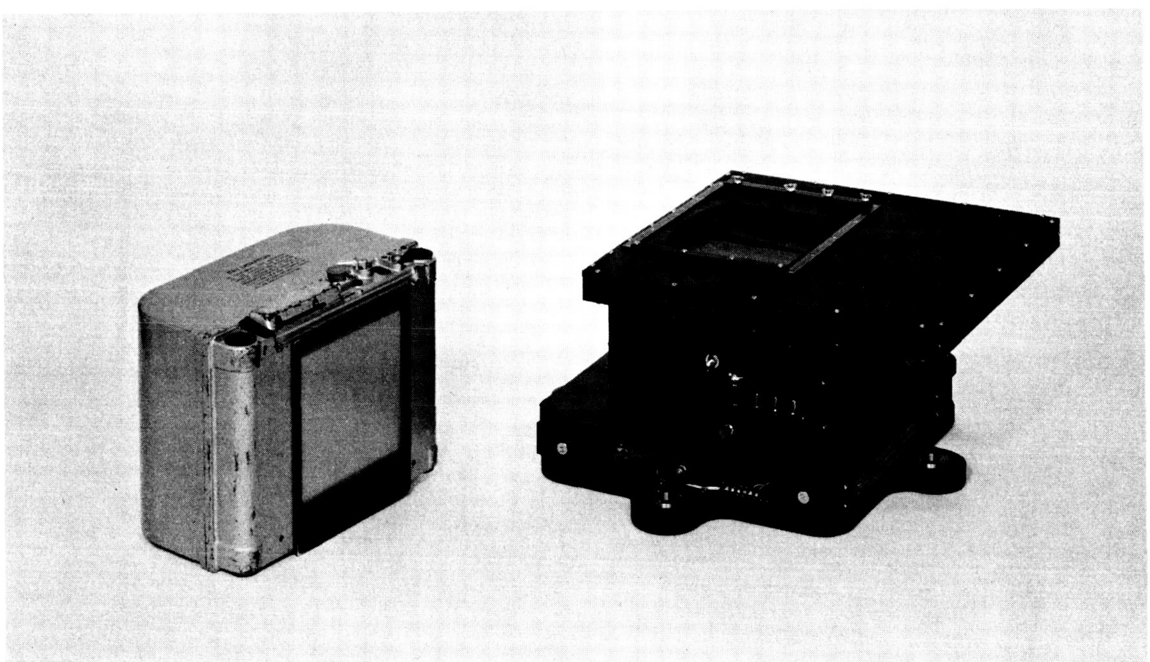


PLATE II VIEW OF CAMERA APPARATUS SEPARATED, SHOWING 9 × 9 INCH APERTURE OF CAMERA

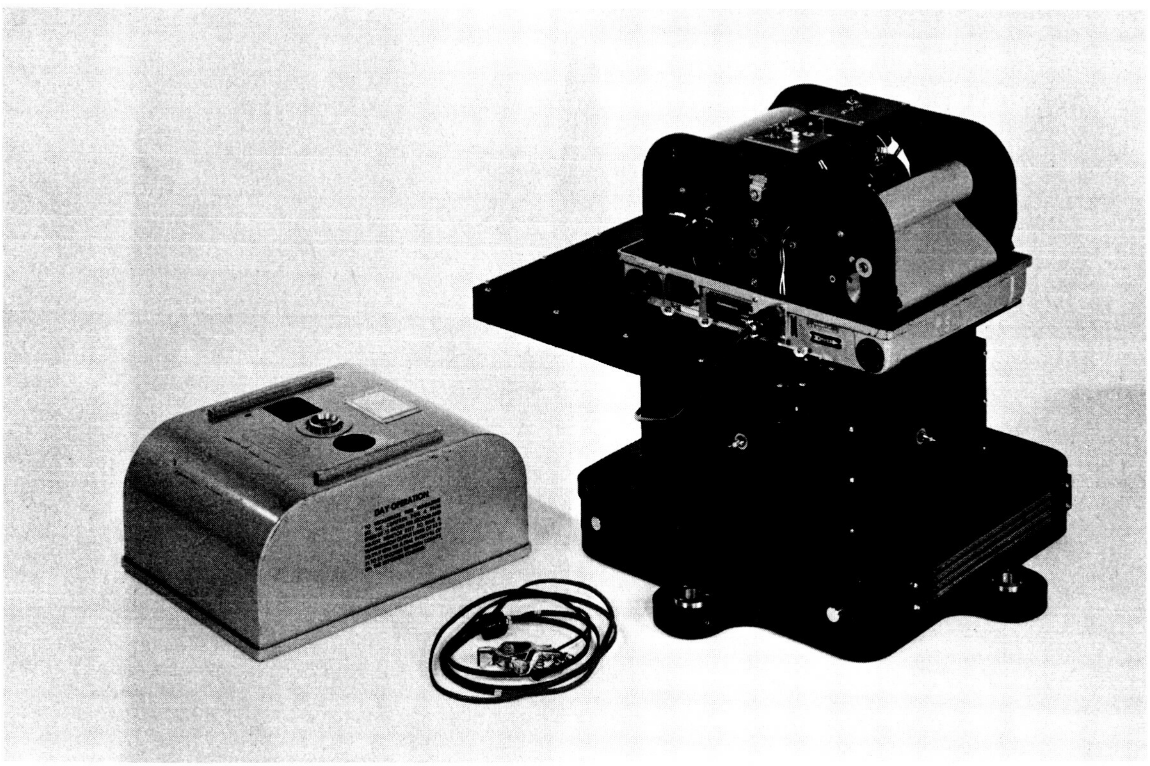


PLATE III VIEW OF CAMERA APPARATUS; COVER REMOVED FROM IMC CAMERA SHOWING INTERIOR PARTS AND ROLL OF FILM IN PLACE

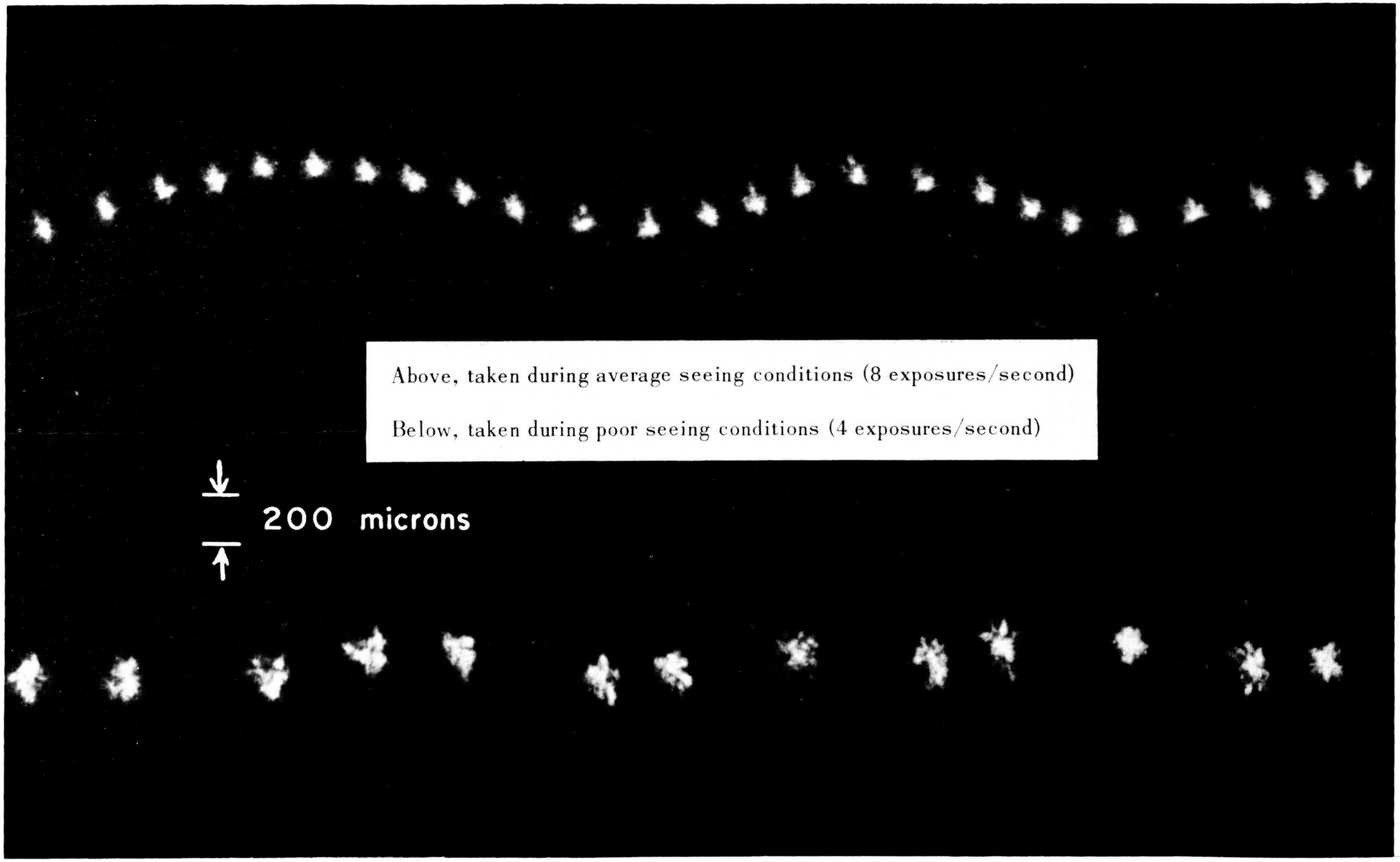


PLATE IV MULTIPLE 1/140-SECOND EXPOSURES OF VEGA, SHOWING SEEING EFFECTS ON STELLER-IMAGE REPRODUCTION

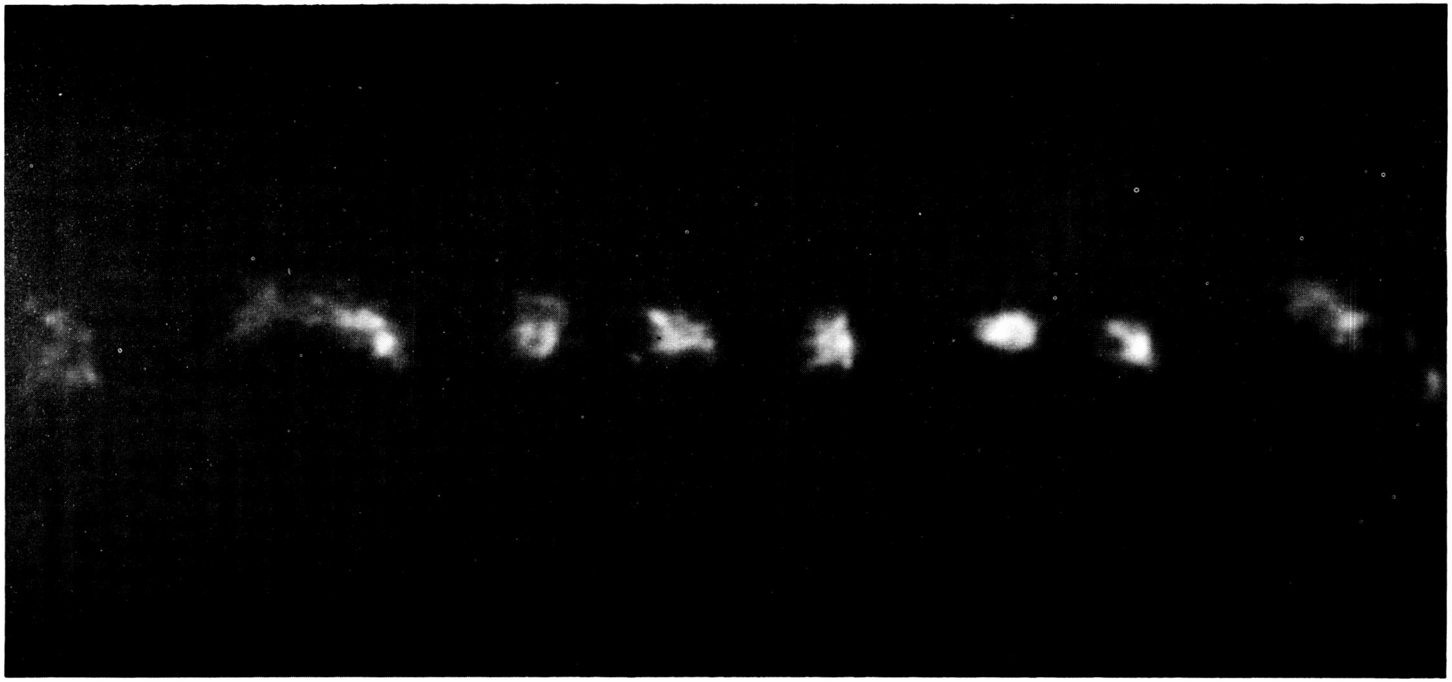
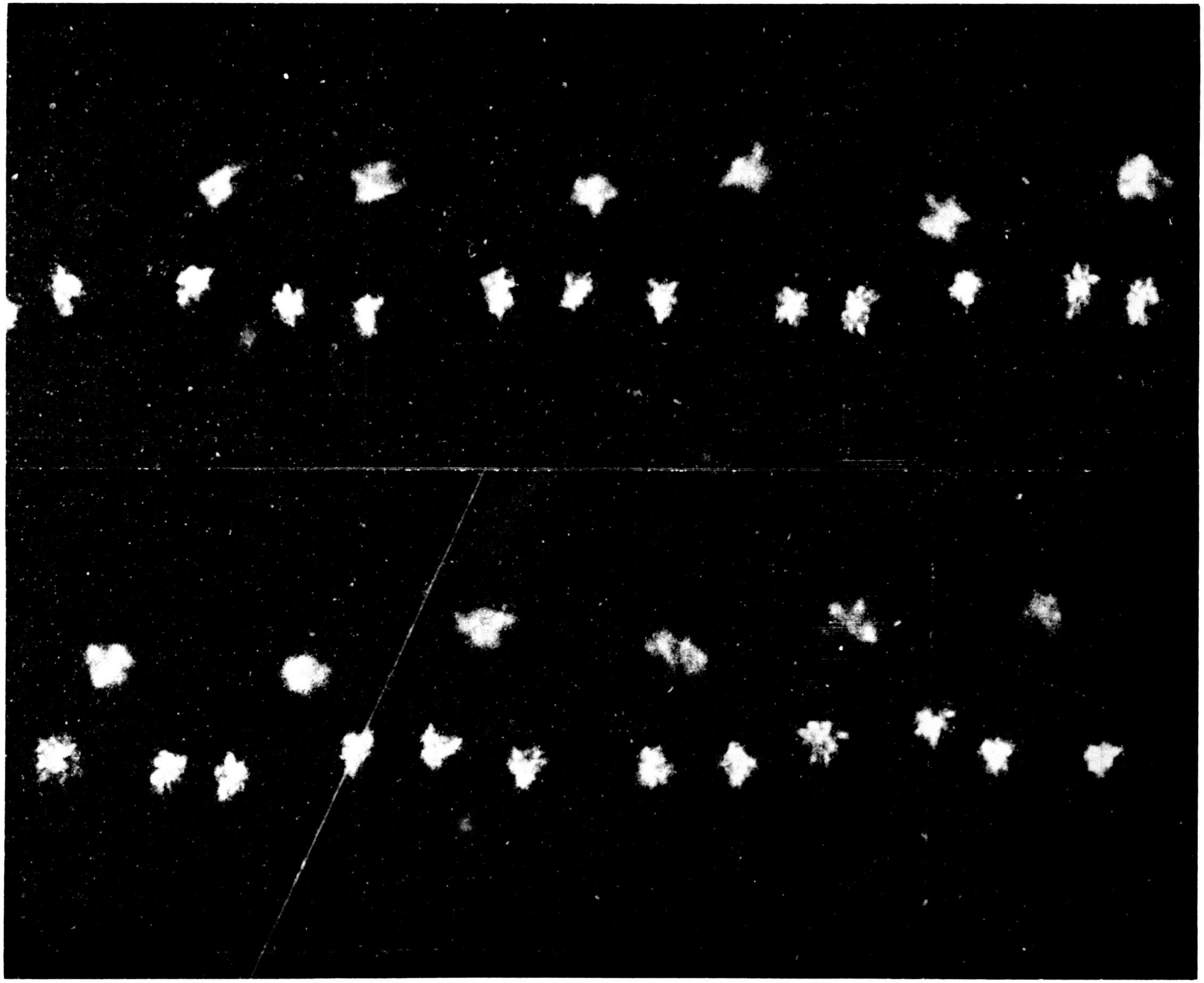


PLATE V   ECHO IMAGES, TAKEN DURING EVENING PASS 8 OCTOBER 1962



E (ECHO)

S (STAR)

E

S

PLATE VI ECHO IMAGES, TAKEN DURING EVENING PASS 23 OCTOBER 1962
(Vega images presented for comparison)

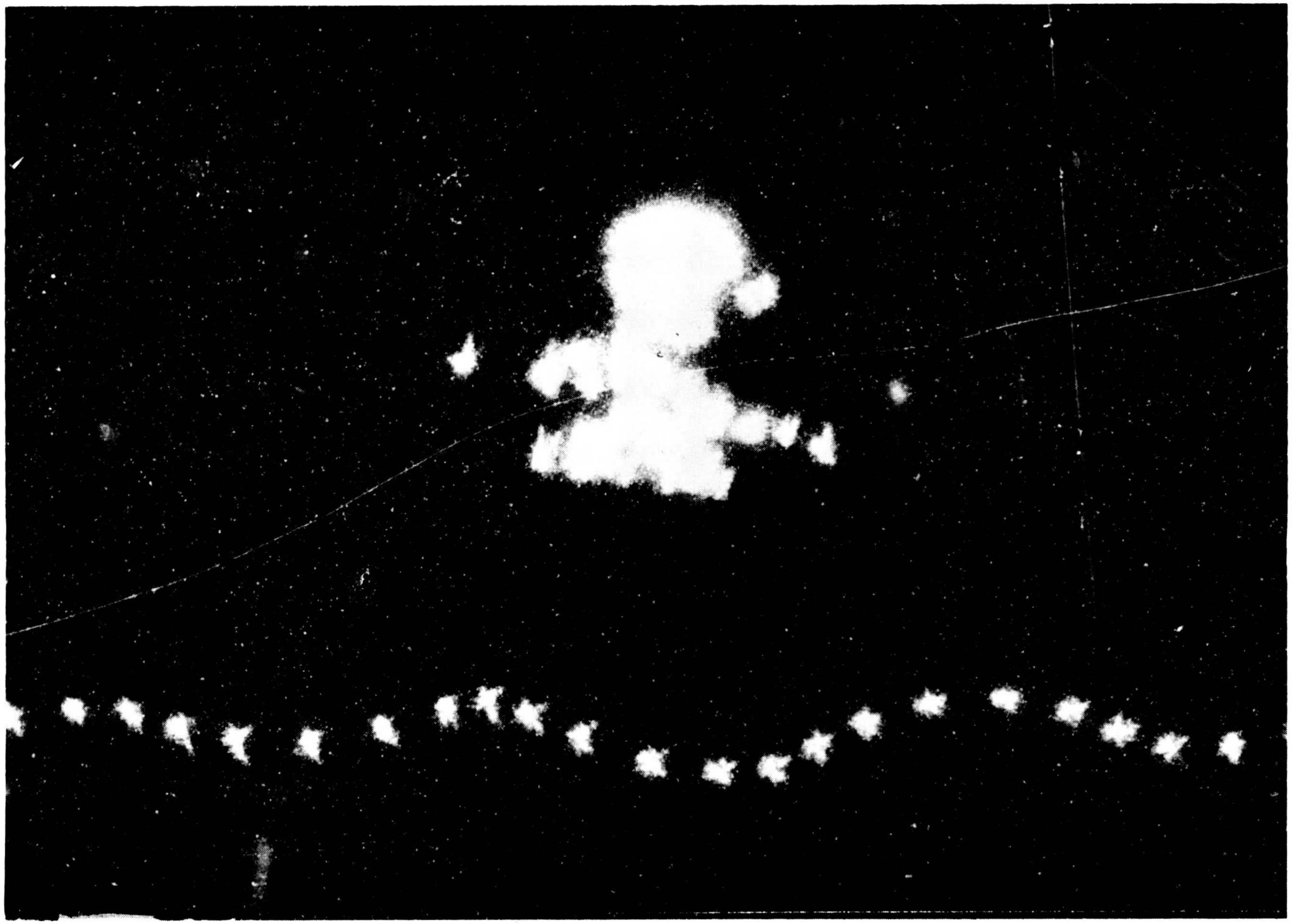


PLATE VII ECHO IMAGES, TAKEN DURING EVENING PASS 24 OCTOBER 1962
(Vega images presented for comparison)

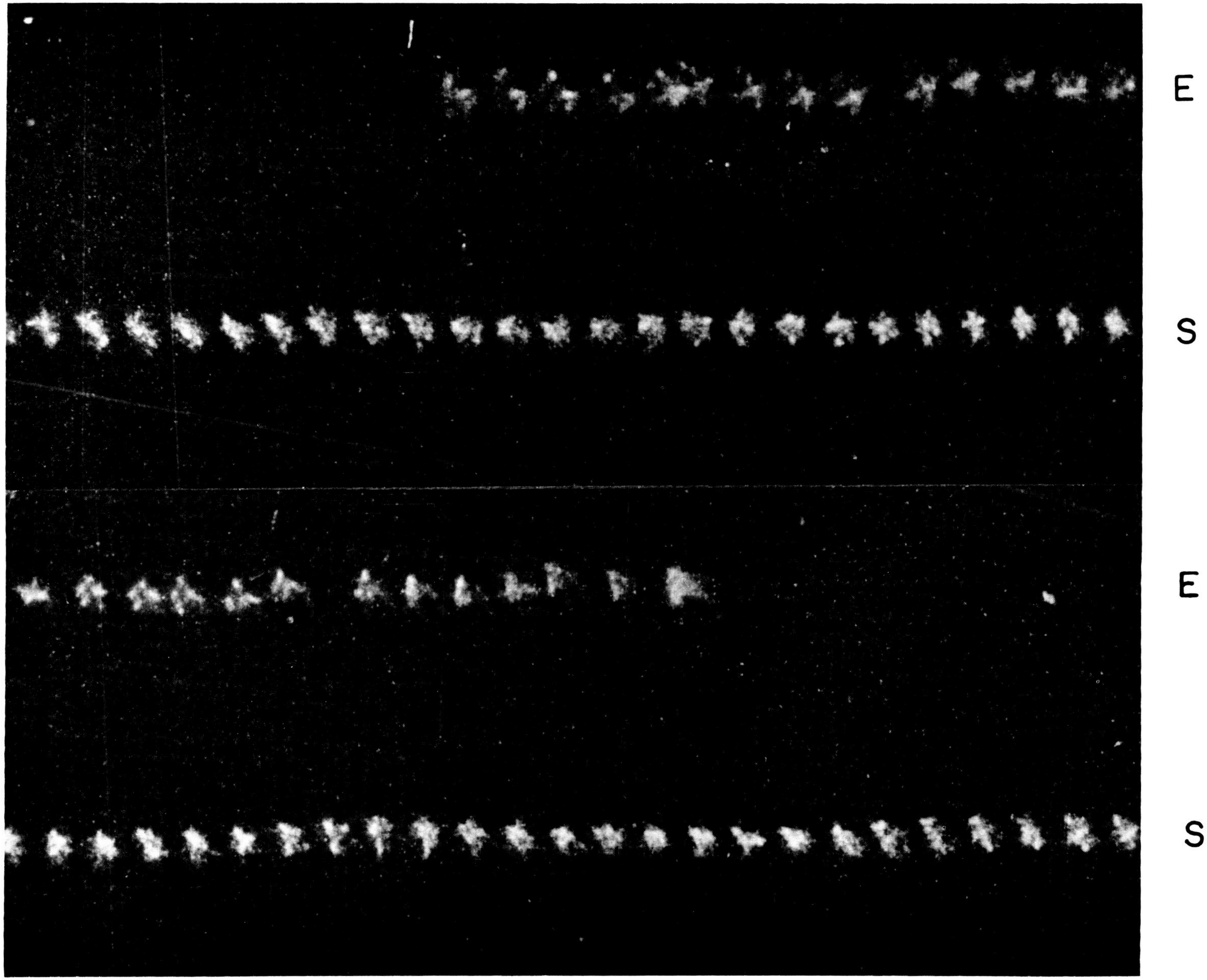


PLATE VIII ECHO IMAGES, TAKEN DURING EVENING PASS 25 OCTOBER 1962
(Vega images presented for comparison)

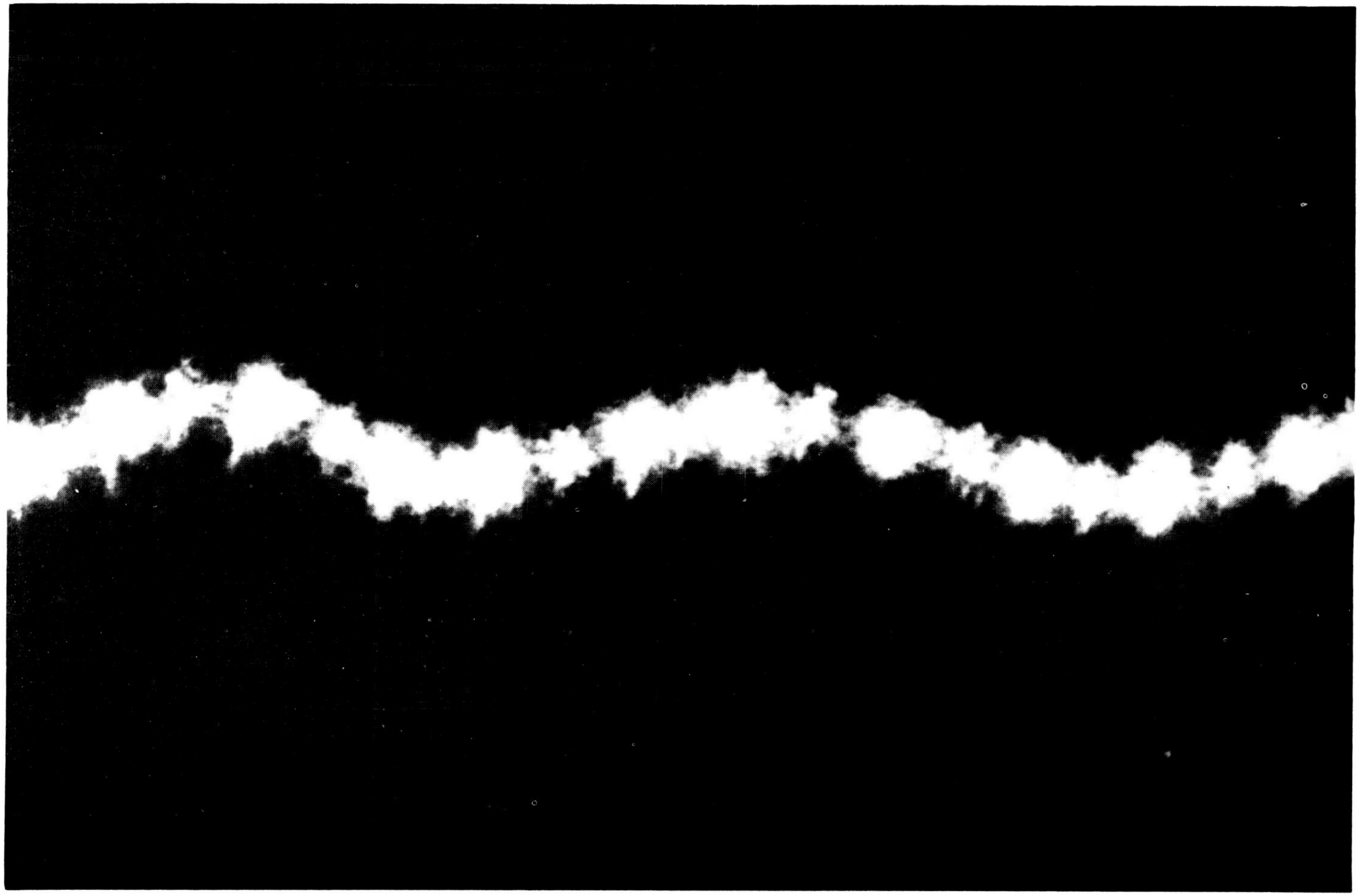


PLATE IX VEGA IMAGES, TAKEN WITH ALTERNATE 1/35- AND 1/140-SECOND EXPOSURE, ILLUSTRATING IMAGE ENLARGEMENT WITH INCREASING EXPOSURE, INCLUDING SEEING EFFECTS

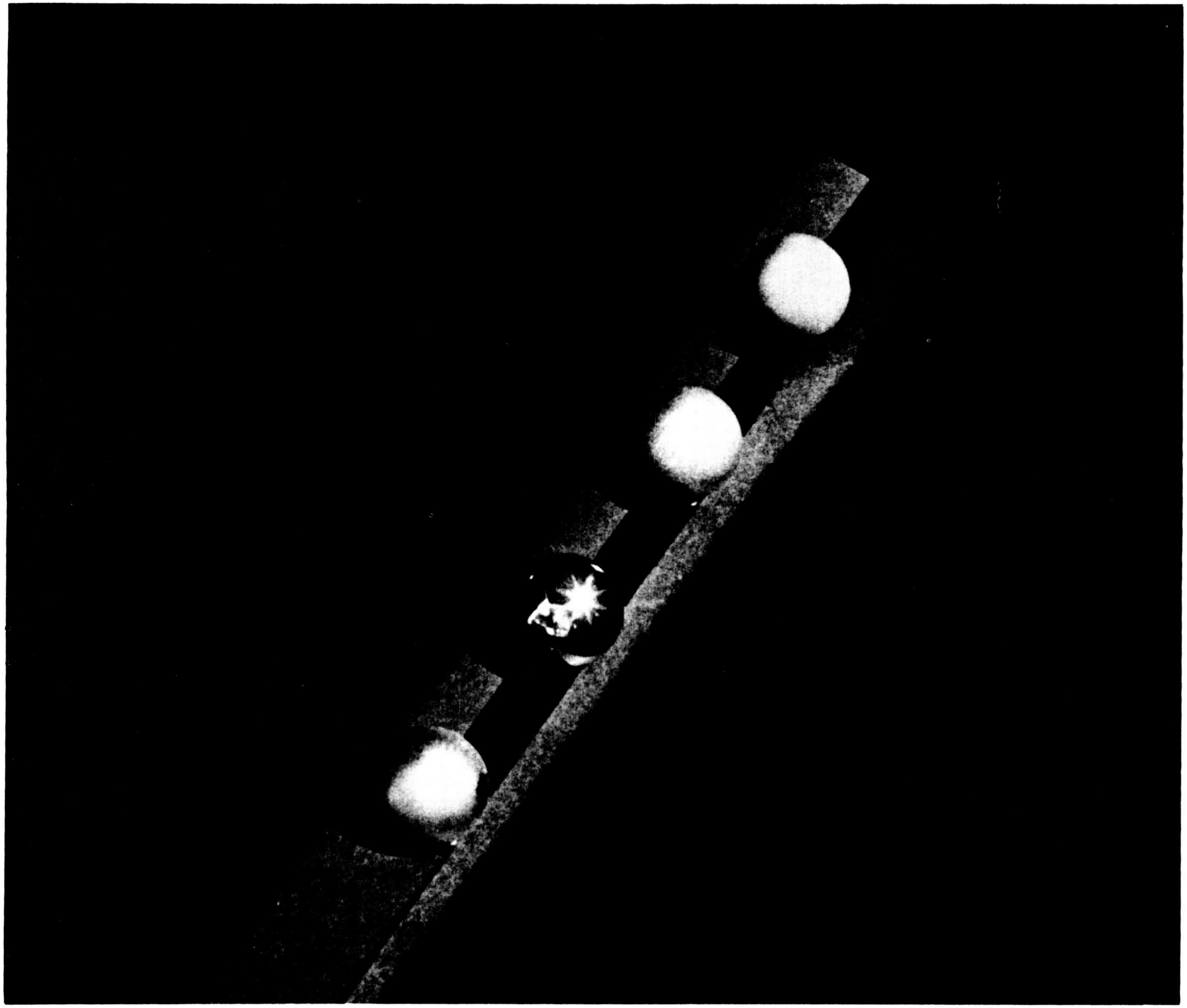


PLATE X FOUR STEEL BEARING BALLS, WITH VARIOUS REFLECTIVE COATINGS, IN A MODEL EXPERIMENT

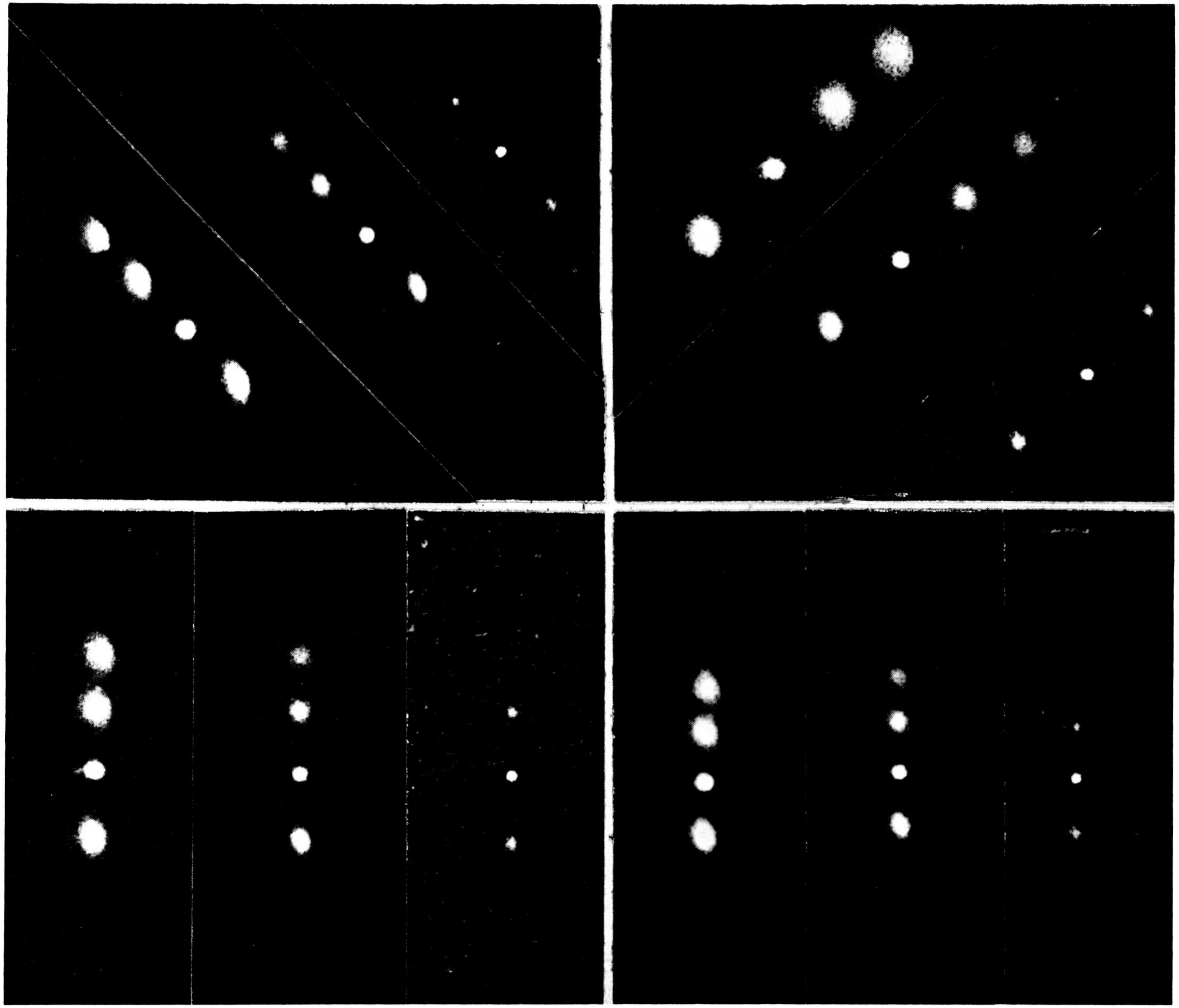


PLATE XI RESULTS OF THE MODEL EXPERIMENT, SHOWING WHAT WOULD BE SEEN ON THE BALLOON SATELLITE WITH DIFFERENT REFLECTIVE COATINGS

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The photograph of the balloon satellite Echo I shown in the Frontispiece is from NASA-Patrick AFB files.